UDC 528.3

METROLOGICAL PROBLEMS OF COORDINATE-TIME SPACE IN SATELLITE AND TERRESTRIAL GEODETIC MEASUREMENTS

I. Trevoho, I. Tsyupak
Lviv Polytechnik National University

Keywords: coordinate system, coordinate-time space, satellite and terrestrial measurements, GNSS-technology.

Statement of the problem

The accuracy of the coordinates of points using GPS/GNSS is estimated at 2-3 mm. The differences between the coordinates of points, that are defined using precise ephemeris by the two daily sessions of GPS-observations, usually processing within 1-4 mm. At the same time, the analysis of daily determinations of coordinates of permanent GPS-points for long periods, such as one year, shows their age or trend changes, periodic oscillations (within 1 cm) and some "rebounds". Based on the study of GPS-observations permanent stations complex (certain number), which are located across the Earth's surface, set an implementation ITRF-YY of terrestrial coordinate system ITRS is [13] to a certain age 20YY. Satellite measurements and coordinate system, that they are processed in, set are dependent on time, therefore they belong to a particular coordinate-time space, where both the coordinate system and the system of time measuring is some way selected and meet certain conditions. As follows, we can speak of a conditional coordinate-time space, that is accepted for a terrestrial coordinate system ITRS.

This coordinate-time space (an implementation of terrestrial coordinate system ITRF) is established as a homogeneous, but the completion or "settlement" of this space by other points geodetic networks of points' that are defined with different precision, turn it into inhomogeneous.

Measurements and values or parameters, that are determined from their study, this includes the coordinates of points and the coordinate system or the coordinate-time space, shall comply with standard units of measurements to provide their unity, precision and unambiguity as basic requirements (principles) of metrology.

Analysis of recent research and publications

In the mentioned coordinate-time space continental, regional, local geodetic networks are created. These include networks of active reference stations of differential GNSS (DGNSS), for example, EUPOS (European Position Determination System) [16], or a part of the network as a local: SAPOS - in Germany, ASG-EUPOS - in Poland, CZPOS - in Czech, SK POS - in Slovakia, UA-EUPOS/ZAKPOS [8] - in Ukraine. Based on a network of permanent and the networks of active reference stations, both the local networks of active reference stations, that are designed to find a solution for the tasks of topography, cadastre, engineering geodesy, and the active geodetic networks for the monitoring of engineering structures develop [12]. Also based on the permanent stations, fundamental geodetic networks for metrological certification of GPS/GNSS-receivers and the control of the precision of methods for determining the parameters of satellite observations are established [10, 17].

Due to the widespread use of GPS/GNSS technology, a concept of a geodetic navigation space arises [7]. In many cases [1, 3] geodetic networks are created by satellite (GPS/GNSS-measurements) and terrestrial (by electronic total station) methods, but processing is often performed separately: at first, the network of reference points is adjusted using satellite observations and geodetic networks, which are created by terrestrial methods, develop between them. Herewith the processing of satellite observations are performed in a coordinate system, that is dependent on time, and terrestrial measurements are performed in a system, which the position of points is constant with time in. Thus, the uniqueness of the solution is violated [7], and therefore the basic principles of metrology are violated too.

Statement of the purpose

The above indicates the need to analyze the possibilities to preserve the accuracy of the reference coordinate system while defining new points and geodetic networks in the accepted system. At the same time, it is necessary to identify the conditions of preservation of the standard measurement unit in measurements, in coordinate system and in geodetic networks, the coordinates of the points of that are defined in the reference coordinate system.

The main material

The principles of metrology. Metrology is designed to provide the preservation of the unity of measurements by means of keeping unit of measurement equal to the standard. Measurements are carried out with errors, therefore the conformity of the unit of measurement of these measurements with the standard one is possible with a certain accuracy.

The coordinate system in a gravitational field. Geodetic measurements are performed to determine the relative location of points of the Earth's surface and their possible changes over time. The location of points in space is determined in the spatial coordinate system, herewith it is known, that the movement is a characteristic of the existence of matter, so it is important for us to know the properties of the relative movement of points in space over time. It known from physics, [5] that the movement can be relative, namely the change of the position of one point relatively to another, or relatively to the coordinate system is determined - on one hand and with the passage of time - on the other hand. The change of the position of a point over time - is the speed of movement. Hence, the study of movement is possible in space and time.

Considering that everything in space moves and changes (moves insignificantly), and this is possible by comparing the state space at different points in time (epochs), so coordinate systems in satellite geodesy are variable over time. Thus, we can note that the study of changes of the position of the points over time takes place in a coordinate-time space.

Space and time are mutually connected values, because movement in space occurs over time. Time is a unit of space, if we know the speed of light as a constant (in vacuum).

In addition, it is known that there is a phenomenon of gravity [2], which affects everything contained within its influence, namely in a gravitational field. The gravitational field has more capacity (influence), when it is closer to the body, that creates (generates) gravity by its weight, namely by the quantity of its potential energy. It is known that the gravitational field also affects the rectilinear movement of an electromagnetic wave, contorting or refracting its trajectory and attracting toward the center of mass. Since body of the Earth has a spheroid shape, a laser beam or collimating ray, which moves between points on the Earth's surface, distorts, "remaining" parallel to the surface, along that it moves , and the corresponding correction for this phenomenon in surveying is called the correction of the Earth's curvature. The coordinate system is implemented by means of the observations of satellites and the measurements between points on the Earth's surface. The Earth's gravitational field acts on satellite or terrestrial measurements, the latter are performed by an electronic total station, as on the electromagnetic waves. For example, due to the Earth's spheroid shape, the beam of light at line lengths longer than 500-600 m, significantly bents [11], turning in a curve of the second order.

The space of a geocentric coordinate system is in the gravitational field of the Earth, which affects the coordinate lines, bending them through changing the saturation of the field with distance from the surface. The influence of the Earth's gravity decreases radially with distance from the surface, but also there is a constant influence of the gravitational fields of the Moon and the Sun and their periodically variable effect, that is caused by the movement of the Moon around the Earth, the Earth's movement along its orbit around the Sun and the rotation of the Earth's body itself around its axis, which has an unequal distribution of mass inside. Thus, the space, in that a system of coordinates is created, is uneven due to the changes in the influence of the gravitational fields of the Earth's, Moon's and Sun's bodies in all its points [5]. The atmosphere has a mass and it also creates an additional gravitational field, that varies with time due to the movement of the masses, as well as due to the changes in the density, that is caused by the changes of the meteorological data (temperature, atmospheric pressure, humidity). Axes of this coordinate system will not be straight lines and scale of the axes of coordinates will be variable, this way the scale is a function of position and time at each point of the space.

If an electromagnetic wave propagates in space at the speed of light, gravity acts instantaneously. This means that gravity does not spread and already exists everywhere, where is a celestial body and to the limit of the effect of its field, which generated by mass. Celestial body moves along the orbit together with its gravitational field. Gravitational interaction between two celestial bodies arises as soon as their gravitational fields reach the tangible interaction. The rate of change (increase or decrease) of the interaction between bodies depends on the relative velocity of the bodies along the line, that connects their centers of mass. Hence, the size of each celestial body composes of three parts: the size of the body itself, the thickness of the atmosphere, if it exists, and the radius of the effect of the gravitational field.

All this affects both the electromagnetic signal and the body of the satellite, which moves under the influence of these effects, as forces, that cause acceleration in its movement. The observer from the Earth's surface performs satellite or terrestrial measurements, based on which he implements a system of coordinates. Thus, the space of the coordinate system will be heterogeneous and uneven, therefore the scale of such coordinate space in each point of it will be different. It is pretty difficult and ambiguous to execute processing of measurements and determine the coordinates of points in space or any Earth's model parameters (shape, size, external gravity field, rotation and orientation parameters of the Earth, its surface tier, movements of continental plates, changes of the Earth's surface, etc.). in such a coordinate system.

Simulation of the coordinate-time space. Even Newton, Lagrange, Hamilton in determining the laws of mechanics, in the derivation of differential equations to describe the movement of the point (body) pointed out the conditions, under that their action can provide the homogeneity of space [5]. The principle of Galilean relativity [5], Lorentz applied for transformations in the inertial coordinate systems, which move with velocities, that are close to the speed of light. The theory of relativity, in which the influence of the body's gravitational field on the deflection of light rays is proved, is based on these transformations.

Special and general relativity theories are used for description of the interaction of bodies and the change of the lengths of lines (intervals) in 4-dimensional inertial coordinate system, which move with velocities, that are close to the speed of light and a large curvature of space with large distances [2]. In small spaces, where the gravitational curvature of lines is not much different from the straight-line Euclidean space, it is enough to use straight-line spatial coordinate systems and the Newtonian potential theory to describe the movement of the satellite in the Earth's gravitational field [14]. Herewith, it is necessary to introduce corrections for relativistic effects both in the movement of the satellite, and in satellite measurements.

Thus, barycentric celestial ICRS and geocentric terrestrial ITRS 3-dimensional coordinate systems are used [6]. Axles of ICRS system are fixed in space and it is implemented as an inertial coordinate system ICRF using the catalog of coordinates of stars and quasars. In this system, the coordinates of the planets and satellites are determined. Coordinates of points on the Earth's surface are determined in the realization of terrestrial coordinate system ITRF, the axles of which are fastened to the Earth's body by the coordinates of permanent stations, that are determined by space geodesy techniques (SLR, LLR, GPS and DORIS), and have a daily rotation. The Earth's coordinate system is also defined using the unit of length (meter), which is coherent with constant speed of light in vacuum. The error of the superimposition of centre of ITRF system with a geocenter ~5 cm [6]. The scale factor, which for the system ITRF is $2\cdot10^{-9}$, characterizes the internal accuracy (harmonization) of both the coordinate system and the geodetic network.

The coordinate system ITRF is time-dependent because of the motions of continental plates, as well as the tides. Therefore, Galilean relativity principle is used to calculate the coordinates of points on different epochs [5] by the formulas

$$\left.\begin{aligned} X_t &= X_{\mathbf{0}} + \dot{X}(t - t_{\mathbf{0}}) \\ Y_t &= Y_{\mathbf{0}} + \dot{Y}(t - t_{\mathbf{0}}) \\ Z_t &= Z_{\mathbf{0}} + \dot{Z}(t - t_{\mathbf{0}}) \end{aligned}\right\},$$

where X_0, Y_0, Z_0 and X_t, Y_t, Z_t – are respectively the coordinates of points on the epoch t_0 and t, $\dot{X}$, $\dot{Y}$, $\dot{Z}$ are the rates of change of coordinates in this system. To take into account the load of tides of solid Earth on the change of the coordinates of points, a corresponding model can be determined. The study of such effects on the coordinates of GNSS-stations has shown [18] that this phenomenon can be simulated with errors 0.1-0.3 mm.

The measured values. The gravitational field and the atmosphere also affect the measurements. The error of distance for the relativistic effect for the GPS-satellites is 10 - 19 mm [4] and the effect on the satellite clock, as a generator of the fundamental frequency (10.23 MHz) of the satellite signal, is $4.55\cdot10^{-9}$ MHz. The relative shift of the clock's frequency of the GNSS-receiver through relativistic effect is on the level of 10^{-12}, that after 3 h leads to an error of the clock around 10^{-9} s (error in distance □30 cm). In addition to these errors, the following also influences the accuracy of the determination of the coordinates of points.

1. The errors of ephemeris of the GPS-satellites currently can be estimated as follows: ephemeris, that come with the satellite signal (broadcast), are about 1 m [15], the precise ephemeris (final-files) are about 2.5 cm.

2. The errors of incorporation of the impact of the troposphere and the ionosphere, are mainly about 1 - 3 cm, but at high solar activity the error of account of the influence of the ionospheric refraction can increase several times.

3. The value of errors of the drift of an antenna's phase center of the GPS-receiver and the multipath of the satellite signal usually depends on the design of the antenna. The change of the phase center is at the level of 1-2 mm for many of today's antennas, the impact of the multipath may be greater, that strongly depends on the situation surrounding the location of the observation point.

Processing of observations. Special software packages are used for processing GPS/GNSS-measurements. The theory of the processing algorithm has usually much better accuracy, than measurements are, but the computer programs of different companies may use different model parameters. And, in addition, the packages of the programs may have different purpose: 1) for high frequency processing of GNSS-measurements and for science research with the possibility to replace or choose models of phenomena, for example, models of incorporation of the troposphere's influence, etc.; 2) for the construction of geodetic networks and for finding solutions of engineering problems; 3) for the topographic survey or navigational determination of place position.

Despite the fact that the precision of algorithms is different, it is still higher than the accuracy of the measurements, but the parameters of models and fundamental constants should be used the same, as standard, that will ensure the unity of the units of measurements, because the values, which define the units of measurements in the physical models, are fundamental constants.

In the case of joint processing of terrestrial and satellite measurements and using appropriate coordinate systems, it is necessary to ensure the uniqueness of their connection. To do this, the coordinates of points, that are identified by terrestrial methods at coordinate system, which is unchangeable with time, should be characterized by the epoch of the definition.

Values, that are measured by terrestrial methods, are determined using satellite technology These values include distances between points, the differences of the altitudes of points or the results of GPS/GNSS-leveling, the determination of altitudes, simultaneously adjusting these with the results of the geometric leveling. To compare these values and their potential use in a joint adjustment, their unit measurement must meet the standard. While adhering the conditions of testing of the geodetic devices, it is also necessary to use the same values of fundamental constants, while individual processing of the measurements (satellite and terrestrial) before a joint adjustment.

Geodetic metrology in the coordinate-time space. Geodetic measurements and the determination of any parameters from their study are performed in a coordinate system at a certain epoch, namely in a coordinate-time space. And this space must also meet the metrological requirements, which means to provide the required accuracy and unity of the measurement unit. In this case, the coordinate-time space becomes the reference for metrological certification of a standard geodetic network, a standard linear geodetic basis and geodetic instruments, that are verified using these standard objects.

The place of a geodetic metrology in the coordinate-time space consists of the following:

1) the provision of the use of standard units of measurement, that are concerted with each other;

2) the adoption and the recommendation for using of the list of fundamental constants and algorithms, which will be used during processing of geodetic measurements and modeling of the impact of the environment on the measurements;

3) the calibration and testing of geodetic instruments for terrestrial and satellite measurements;

4) the creation and metrological certification of standard fundamental geodetic networks and linear bases for testing geodetic devices, including GPS/GNSS-receivers;

5) the provision of unity of the unit of measurement at the joint adjustment of the results of terrestrial and satellite measurements.

Thus, the accuracy of the determination of coordinates of permanent points and their temporal changes, as fiducial points of the coordinate system, indicate the accuracy of the realization of the coordinate system in time, namely in a coordinate-time space. The level of geodynamic changes is bigger than the level of accuracy of measurements less than on an order, and, consequently, the same attitude is between the accuracy of the measurements and modeling of the atmosphere and gravity field. Therefore, the impact of these effects on the accuracy of measurements should be the one more task of metrology.

Conclusions

1. The realizations of the global geocentric coordinate system ITRF are based on standard units of measurements (meter and the speed of light in vacuum), that adjusted with each other.

2. The metric of coordinate-time space in ITRF coordinate system is defined by the reference coordinates of points, which fixed at a certain epoch and were used in its creation.

3. Determining of the coordinates of new points in this coordinate system can be achieved through simultaneous observation of satellites GPS/GNSS on those reference stations and points of geodetic networks, whose location needs to be determined. Herewith, ephemeris of GNSS satellites must be determined in the same coordinate system.

4. It should be noted, that the new points, whose coordinates are defined in this realization of the Earth's coordinate system ITRF, do not implement the coordinate system itself. This is because the addition of new points to the implemented coordinate system changes the system itself.

5. The checking of this can be done by determining the parameters of the transformation between the coordinates of points, that implement the coordinate system, and their new definition at fixed coordinates of points, which are added using them as input.

6. Geodetic network of points, that are determined in a particular coordinate system, do not take part in the implementation of the system of coordinates themselves. This is caused by the bigger absolute errors of coordinates of determined points in a given coordinate system.

7. The increase of the absolute errors of coordinates of points does not affect the internal precision of the geodetic network.

8. Thus, we can state that the realization of ITRF coordinate system, using new points, that are determined in the same system, at least, already would not be homogeneous, and its overall accuracy, using all the points, that are defined in the coordinate system, reduces.

9. The use of the networks of active reference stations to determine the coordinates of points in real-time or with processing GPS/GNSS-measurements after observations gives the opportunity to determine the coordinates of points with even greater absolute errors of coordinates of new points in a particular implementation of Earth's coordinate system ITRF.

10. The change of the scale factor of the coordinate system with new points characterizes the accuracy of this system.

References

1. Boyko E.H. Metody sovmestnoy obrabotky lokal'nykh nazemnykh y sputnykovykh heodezycheskykh setey/ Boyko E.H., Zymyn V.M., Hodzhamanov M.H. //Heodezyya y kartohrafyya. – 2000. – # 11. – S.11–18.

2. Bronnykov K. Postulaty otnosytel'noho myra // www.vokrugsveta.ru/vs/article/330/.

3. Vynohradov A.V. Sovmestnoe prymenenye sputnykovykh pryemnykov y эlektronnykh takheometrov pry sozdanyy planovoho obosnovanyya na zastroennykh terrytoryyakh /A.V. Vynohradov, A.V. Voytenko, M.S.

Kupryyanov// Heodezyya y kartohrafyya. –2007. – # 7. – S.33–35.

4. Hlobal'na systema vyznachennya mistseznakhodzhennya (GPS). Teoriya i praktyka/ B. Hofmann-Vellenhof, H. Likhtenehher, D. Kollinz. Per. z anhl. tret'oho vyd. pid red. Ya.S. Yatskiva.- K.: Nauk. Dumka.- 1995.- 380 s.

5. Ivanov B.O. Konspekt lektsiy iz teoretychnoyi mekhaniky: navchal'nyy posibnyk /B. O. Ivanov, M. V. Maksyuta.– K.: Vydavnycho-polihraf. tsentr «Kyyivs'kyy universytet».- 2012.– 207 s.

6. Korsun' A.O. Byuleten' A Ukrayins'koho tsentru vyznachennya parametriv oriyentatsiyi Zemli// http://www.mao.kiev.ua/poz/bul_gid1.htm

7. Mohyl'nyy S. Sovmestnaya obrabotka nazemnykh y sputnykovykh heodezycheskykh yzmerenyy v lokal'nykh setyakh /S. Mohyl'nyy, A. Sholomnytskyy //Suchasni dosyahnennya heodezychnoyi nauky ta vyrobnytstva.- L.: Nats. Un-et «L'vivs'ka politekhnika».- 2009.- Vyp. I (17).- S. 122-131.

8. Savchuk S. Stanovlennya merezhi aktyvnykh referentsnykh stantsiy ZAKPOS /S. Savchuk, I.Prodanets', I. Kalynych // «Novi tekhnolohiyi v heodeziyi, zemlevporyadkuvanni ta lisovporyadkuvanni». Materialy IV Mizhnarodnoyi naukovo-praktychnoyi konferentsiyi (m. Uzhhorod, 21-22 trav. 2009).- Uzhhorod: Vyd-vo „Karpaty”, 2009.- S. 6-8.

9. Trevoho, I. Zabezpechennya metrolohichnoyi atestatsiyi suchasnoyi heodezychnoyi tekhniky na naukovomu heodezychnomu polihoni / I. Trevoho, I. Tsyupak, V. Kupko // Suchasni dosyahnennya heodezychnoyi nauky ta vyrobnytstva.- L.: Vyd.-vo L'vivs'koyi politekhniky.- 2011.- Vyp. II.- # 22.- S. 49-51.

10. Trevoho, I.S. Suchasni vymohy do metrolohichnoho zabezpechennya etalonnoyi fundamental'noyi heodezychnoyi merezhi dlya povirky GNSS-pryymachiv/ I.S. Trevoho, I.M. Tsyupak // Suchasni dosyahnennya heodezychnoyi nauky ta vyrobnytstva.- L.: Vyd.-vo L'vivs'koyi politekhniky.- 2013.- Vyp. I.- # 25.- S. 40-42.

11. Trevoho I.S. Osoblyvosti metrolohichnoyi atestatsiyi etalonnykh heodezychnykh bazysiv/ Trevoho I.S., Tsyupak I.M. //Suchasni dosyahnennya heodezychnoyi nauky ta vyrobnytstva.- L.: Nats. Un-et «L'vivs'ka politekhnika».- 2014.- Vyp. I (27).- S. 29-33.

12. Tretyak K.R. Do pytannya nadiynosti monitoryn-hovykh heodezychnykh merezh/ K.R. Tretyak, I.R. Savchyn// Heodeziya, kartohrafiya i aerofotoznimannya”.- L'viv: NU ”L'vivs'ka politekhnika”.- 2013.- Vyp. 77.- S. 122-126.13. Altamimi et al., The Terrestrial Reference frame and the Dynamic Earth //EOS, Transactions, American Geophysical Union, Vol. 82, No25, June 19, 2001, P. 273.

14. Bjerhammar A. Relativistic Geodesy// NOAA Technical Report NOS 188 NGS 36.- Sept. 1986.

15. http://igscb.jpl.nasa.gov/components/prods.html.

16. Rosenthal G. EUPOS – European Position Determination System// “The Geodetic Infrastructure in Europe – today and tomorrow”.- Umea, Sweden, 22-23 June 2011.

17. Trevoho, I.S. Prospects of metrological provision linear geodetic of measurements on the geodetic test field / I.S. Trevoho, I.M. Tsyupak // Reports on Geodesy.- 2013.- Vol. 94.- No. 1.- Warsaw University of technology.- Pp. 56-63.

18. Yuan L. The tidal displacement field at Earth's surface determined using global GPS observations /L. Yuan, B. Fong Chao, X. Ding, P. Zhong // Journal of Geophysical Research: Solid Earth.-2013.- V. 118, No. 5.- P. 2618–2632.

Metrology of coordinate-time space

I. Trevoho, I. Tsyupak

In this article reviewed the metrological aspects of the Earth's coordinate system ITRF, maintaining its accuracy in determining new points and geodetic networks in this system.